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Assessment of pile driving refusal using the standard penetration test

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ABSTRACT: The design of driven pile foundations involves an iterative process requiring an initial estimate of the refusal level to determine the depth of boreholes for subsequent analyses. Current procedures for determining borehole depths incorporate parameters typically unknown at the investigation stage. Thus, a quantifiable procedure more applicable at this preliminary stage would provide greater confidence in estimating the founding level of driven piles. This paper examines the effectiveness of the Standard Penetration Test (SPT) in directly estimating driven pile refusal levels. A number of significant correlations were obtained between SPT information and pile penetration records demonstrating the potential application of the SPT. Results indicated pile penetration was generally best described as a function of both the pile toe and cumulative shaft SPT values. The influence of the toe SPT increased when piles penetrated rock. A refusal criteria was established from the results to guide both the estimation of borehole depths and likely pile lengths during the design stage.

1 INTRODUCTION

The practice of driving piles to refusal (ie towards the pile's structural limit) is common in Australia. This is due to the relatively shallow rock stratum across the continent, which has often presented the option of driving to refusal as cost effective in instances where deep foundations are required.

The accurate estimation of the refusal level is necessary to determine the depth of boreholes for subsequent foundation design. A borehole that is terminated above the pile founding level is not sufficient for design, however drilling to a depth significantly beyond the required level is costly to the investigation. Current investigation procedures require boreholes to be drilled to a minimum depth corresponding to the level at which 10 % additional stress occurs, or either two to four times the likely pile width or 3 to 5 m below the founding level. Many of these parameters are unknown at the time of the investigation; hence, the drilling site supervisor is required to make an initial judgment regarding the likely founding level – usually on the basis of a "competent" founding material. Thus, a quantifiable procedure more applicable at the investigation stage would introduce greater confidence in estimating the refusal level. This would provide a reference level below which additional drilling could be undertaken to cater for the zone of stress influence and uncertainties at the time of drilling concerning the type/size of pile.

This paper examines the effectiveness of the SPT in directly estimating the refusal level of driven piles. A focus has been placed herein on refusal in rock, however the influence of other substrata materials on pile penetration has also been explored. The SPT was chosen due to its common use and wide integration with standard geotechnical investigation procedures. Often, where coring is likely to lead to significant core loss in weak rock there is also a need to rely on SPT values to provide quantifiable data for these regions.The analysis utilised investigation and pile driving records obtained from bridge sites across South East Queensland (SEQ), Australia with the aims to:

- Assess the role of pile toe and shaft SPT results in estimating pile penetration;
- Investigate the influence of substrata conditions (eg rock lithology and weathering, predominantly cohesive and cohesionless strata) on pile penetration; and
- Analyse potential relationships between SPT information and pile refusal levels in rock to develop preliminary refusal criteria.

The analysis presented herein is an extract from a detailed investigation by Adams (2009) concerning the estimation of refusal in rock using the SPT.

2 BACKGROUND

Pile refusal involves the driving of piles towards their structural limit. The level at which this occurs is a function of both the driving resistance and structural capacity of the pile.

The driving resistance is primarily influenced by the substrata conditions, however it is also affected by a number of factors concerning hammer, cushion, pile and substrata components (Crapps, 2008). The resistance is typically expressed as the permanent penetration per blow (ie pile set) for a given depth within the substrata (Warrington, 2007).

The structural capacity of the pile during driving is dictated by allowable peak compressive and tensile stresses – a product of the structural characteristics of the pile (Crapps, 2008). The induced stresses are a primary function of hammer energy, although the driving equipment setup, use of additional driving measures as well as the ground conditions also influence the peak stresses induced (GEOCED, 1997). These components are typically expressed as a minimum permanent penetration (pile set) per blow for application in the field.

Pile penetration is also dependent on the type of pile, for example timber piles are typically unable to accommodate the high driving stresses tolerated by steel piles. Moreover, for concrete piles a pile set of 2 to 5 mm typically indicates the limits of drivability whereas for steel H piles a pile set of 1 to 2 mm is often achievable before pile damage occurs. However, more rigorous analyses are generally employed to assess pile driveability and include (Manningan et al., 1993):

- Wave equation analysis;
- Dynamic testing and analysis; and
- Load testing.

3 DATA ANALYSIS

Data from investigation and pile driving records for sites across SEQ was used to assess potential relationships between the pile set (final permanent penetration per blow) and corresponding SPT information. In the case of SPT refusal extrapolated values were used by directly converting to a 300 mm standard penetration. A total of 403 points from 67 impact driven prestressed concrete (PSC) piles across 17 bridge sites were used in the analysis. Piles were generally 450 to 550 mm octagonal. Refusal (final set) values were also recorded from the driving records for use in the development of preliminary refusal criteria in rock. The median and maximum value from the surface level to the top of extremely weathered rock was 14 m and 25 m for this data set respectively. Hammer energy and type were not considered as it is generally unknown at the investigation stage; data consisted of piles driving using impact hammers.

The influence of toe and shaft material was assessed by manipulating the SPT data inline with three models; where corresponding SPT values (T_1, T_2,…T_{n-1}, T_n) and set values (S_1, S_2,…S_{n-1}, S_n) are noted along the pile depth (T_n and S_n denoting values at the pile toe):

- $\text{Model 1}: S_n \quad \text{vs.} \quad T_n$
- $\text{Model 2}: S_n \quad \text{vs.} \quad \sum_{i=1}^{n} T_i$

– Model 3: S_n vs. $(Z \times T_n) + \sum_{i=1}^{n} T_i$

The factor (Z) used in Model 3 sought to cater for differing influences between pile toe and shaft material and was selected through iteration. The cumulative shaft SPT component used in Models 2 & 3 was normalised to cater for differing SPT sampling frequencies between investigations.

The data was subsequently categorised based on pile toe and predominant substrata material to assess the influence of different materials. Categories for Model 3 were based on Model 2 as more significant correlations were obtained compared to Model 1. The data allowed for the following categories for each model:

- Model 1 (General): Clay (62 points); Sand (127 points); Gravel (159 points); Rock (54 points)
- Model 1 (Rock): Extremely Weathered Rock (XW) (43 points); Highly Weathered Rock (HW) (9 points); Sandstone (42 points); Shale (8 points)
- Models 2 & 3: Cohesive (112 points); Cohesionless (291 points)

A number of statistical models were assessed (ie power, exponential and logarithmic functions). The power function provided the most significant correlations (highest R-Squared value) and thus has been depicted herein. The logarithmic function provided marginally improved correlations only when assessing general and detailed rock categories and has been included in these instances. A process of removing outliers was not generally adopted in the analysis, however, in the case of general and detailed rock categories one clear outlier was removed.

3.1 *Influence of pile toe SPT on pile set*

Correlations between the toe SPT and set value are summarised in Figure 1. For general material categories this model provided the weakest correlations. R-Squared (R^2) values were approximately 0.3 for clays, sands and gravels. However, a notably higher value of 0.45 (0.5 using a logarithmic function) was obtained for the general rock category. This indicates that for piles penetrating rock the toe SPT has an increased influence on the pile set; consistent with the pile bearing analogy whereby piles bearing on rock are often designed as end bearing elements.

The magnitude of final set values were smaller for the rock category (2 to 5 mm) compared with others and is indicative of driving piles to refusal when penetrating rock.

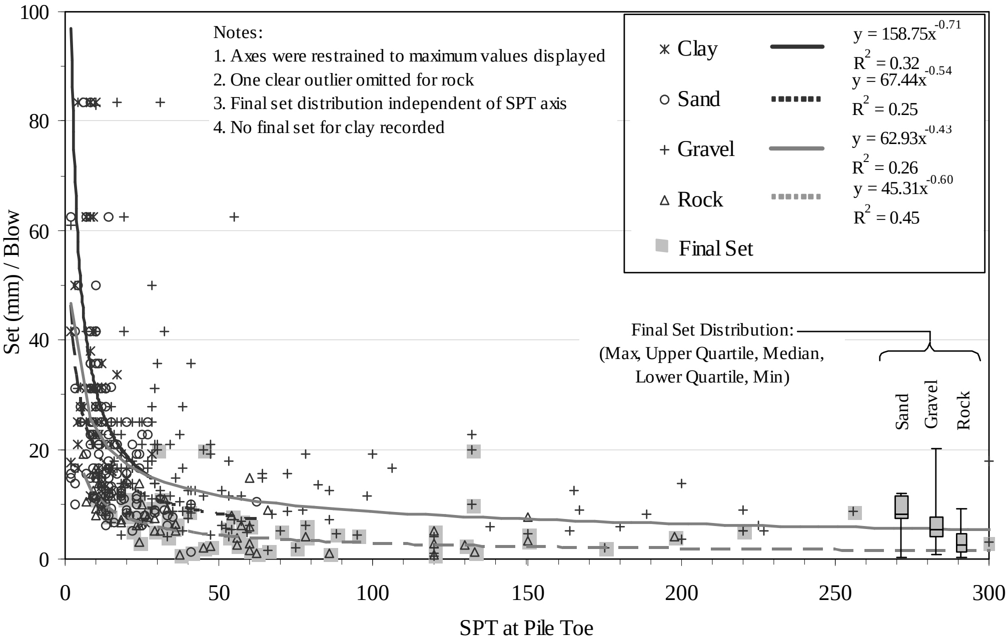

Figure 1. Pile toe SPT and set correlations

Assessment of detailed rock categories (ie weathering and lithology) resulted in improved correlations between toe SPT and set values (Figs 2 - 3). Further improvement was exhibited by using a logarithmic function to describe the data in all but one case. Due to the inconsistent and marginal nature of these improvements relationships using the power function remained the focus.

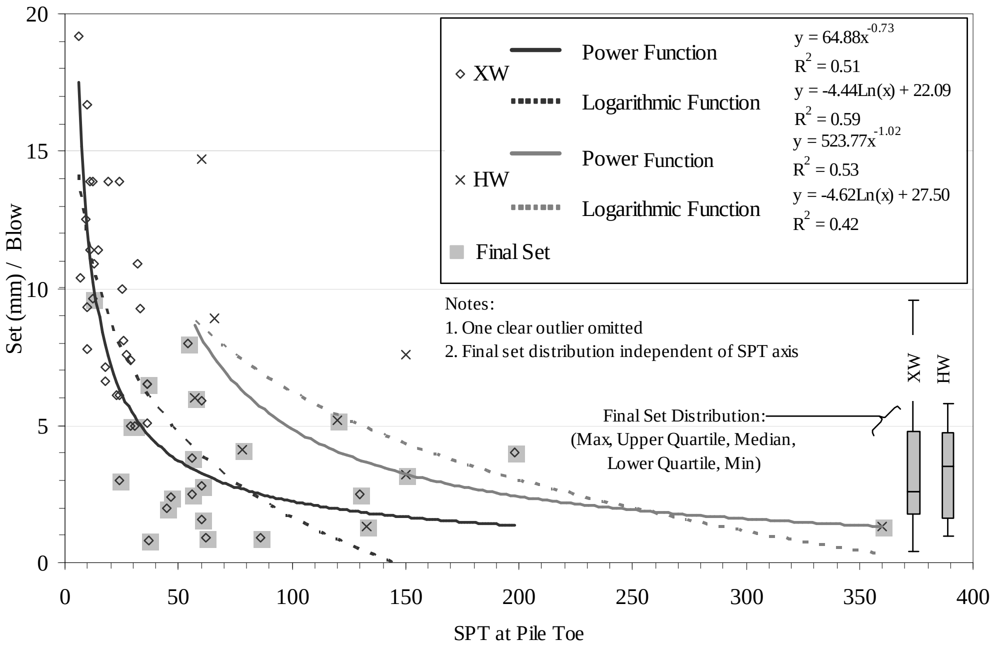

Figure 2. Pile toe SPT and set correlations based on rock weathering

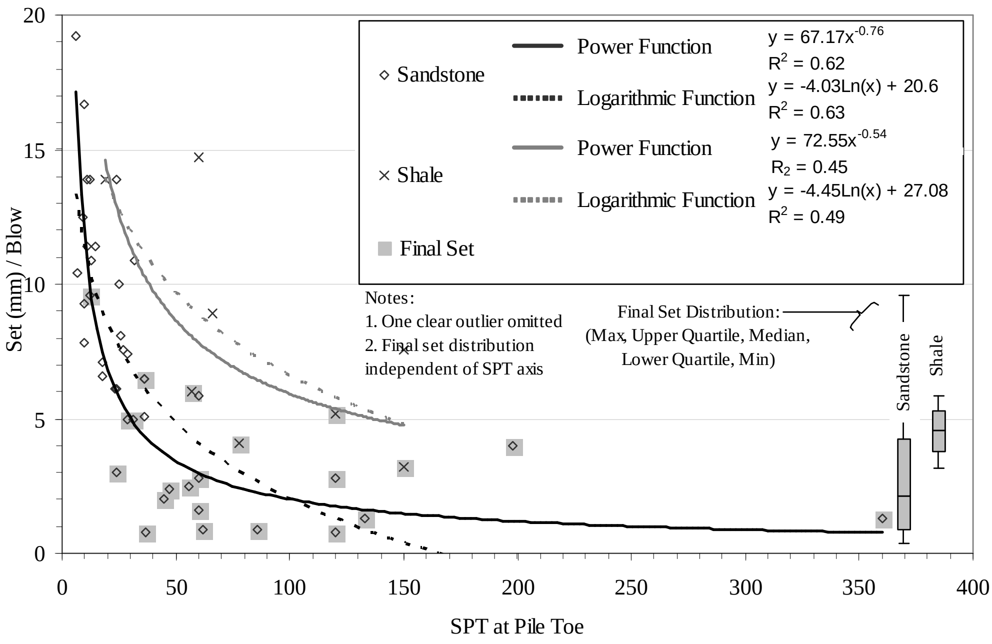

Figure 3. Pile toe SPT and set correlations based on rock lithology

Significant correlations (ie ≥ 0.5) were obtained for both weathering and lithology indicating both affect set values. The highest correlation was obtained for rock lithology (R^2 of 0.62) suggesting its greater influence on pile set. However, this was inconclusive as the data generally consisted of XW sandstone and HW shale rather than an array of different weathering grades for each lithology and vice-versa.

Despite the distribution of the data, the results indicate that for an equivalent SPT value a larger set would be obtained in HW shale compared with XW sandstone. However, due to the small HW shale data set this may be a function of project/site specific conditions (eg differing hammer energy, pile size).

The distribution of final set values in terms of rock lithology demonstrate that a smaller final set generally occurred in sandstone compared with shale. In terms of rock weathering, little difference was exhibited between the final set values of XW and HW materials. These results may also be influenced by project/site specific conditions due to the small data sets for HW rock and shale categories noted previously.

3.2 *Influence of pile shaft SPT on pile set*

Improved correlations were obtained when assessing the relationship between cumulative shaft SPT results and set values (Fig. 4). R^2 values of 0.52 and 0.40 were obtained for predominantly cohesive and cohesionless strata respectively. The improved results (compared with toe SPT relationships) indicate that the cumulative shaft SPT values generally have a greater influence than the toe SPT on set values.

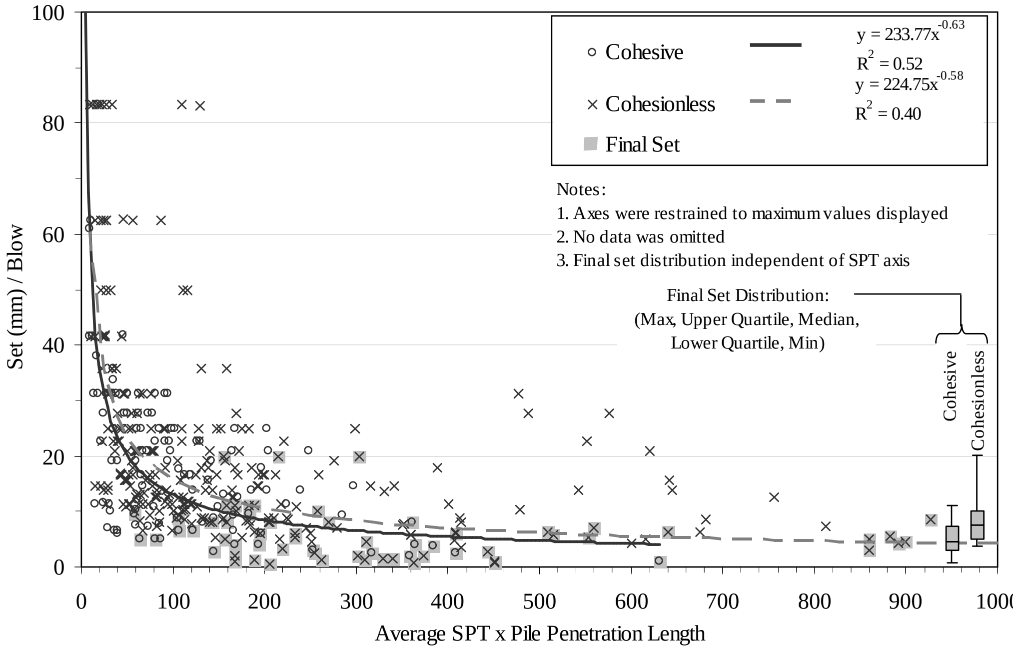

Figure 4. Pile shaft SPT and set correlations

3.3 *Influence of combined pile toe and shaft SPT on pile set*

Assessment of the combined influence of pile toe and shaft SPT values on pile set provided the strongest correlation of the three models (Fig. 5). A marked improvement (compared with independent shaft SPT relationships) was achieved for the cohesive category (R^2 of 0.70). However, only a marginal improvement was achieved for cohesionless material (R^2 of 0.41). Overall, the results indicate that the pile set is generally best described as a function of both the pile toe and shaft SPT results.

The lower correlation for cohesionless material may be due to the relative scale of the SPT and driving processes; a granular object obstructing the SPT driving head can significantly increase the SPT result but not lend to an increase in the driving resistance due to the notably larger size of the pile.

A toe SPT factor (refer to Section 3) of 13.0 and 1.2 was used for cohesive and cohesionless material respectively. Although these factors are only empirical, relatively they suggest that the toe SPT has greater influence on pile set for piles driven in predominantly cohesive strata. This is consistent with the weakening of the clay material due to shearing, remoulding and increased pore water pressure attributed to the driving process. In contrast, a densification is experienced for cohesionless material along the pile length as it is driven, lending to an increase in shaft resistance.

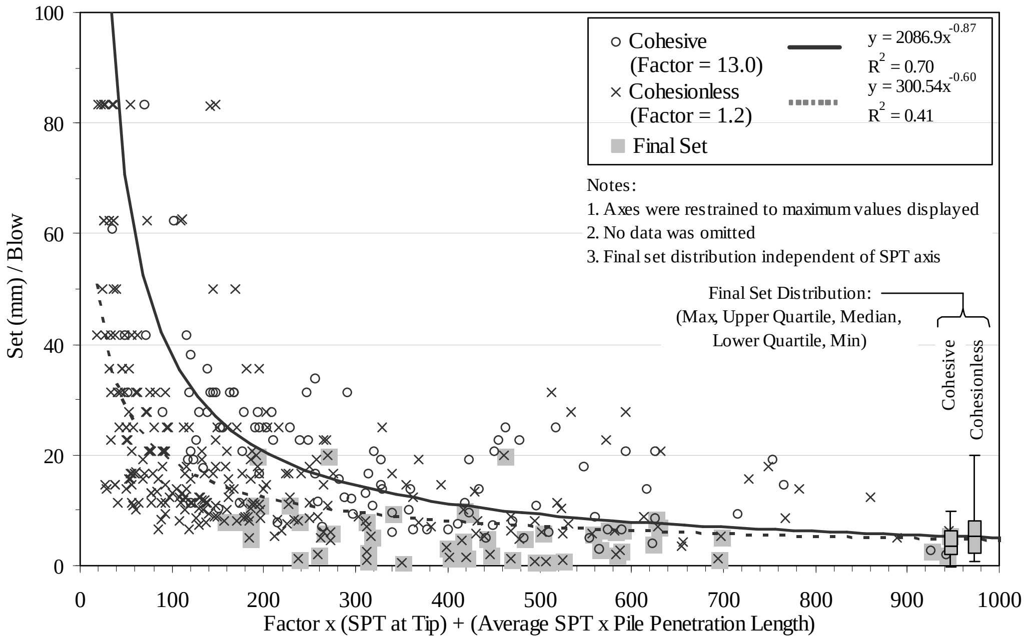

Figure 5. Combined pile toe and shaft SPT and set correlations

A practical illustration of pile set estimation using the combined toe and shaft SPT model for predominantly cohesive strata is provided in Figure 6; the examples incorporate data used to develop the original model.

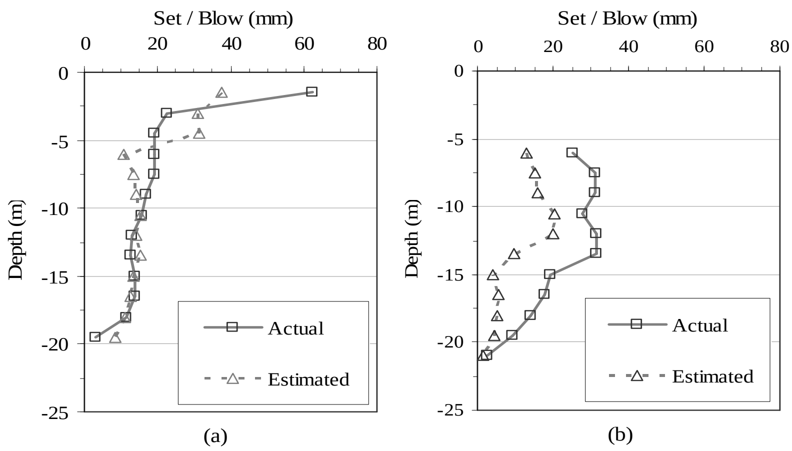

Figure 6. Comparison of actual and estimated pile set using combined toe and shaft SPT model for predominantly cohesive material: Example of (a) Good and (b) Poor set estimation

The first example illustrates a generally accurate estimation of pile set, with a relatively close fit (within 5 mm of actual set values) at depths greater than 8 m. Similar accuracy is not demonstrated by the second example with set values consistently underestimated (approximately 10 to 15 mm) along the entire pile length, although this decreases with depth. This underestimation may be due to a number of factors not considered in this model (eg larger hammer energy, smaller diameter pile). Lower accuracy at shallow depths is demonstrated in both examples. This may be attributed to greater variability in setup and conditions at earlier stages of driving illustrated by the greater variance in set values at lower SPT ranges (eg for a combined SPT value of 110 the set values of recorded points range from 10 to 60) (Fig. 5). However, the use of a power function to describe the data may also contribute to this inaccuracy. In the lower SPT range (ie 0 to 150) (Fig. 5) the model is more sensitive; a marginal change in SPT values results in a notable change in estimated set. However, this characteristic does not detract significantly from the application of the model, with greater accuracy and less sensitivity demonstrated at larger depths where refusal is more likely to occur.

3.4 *Pile refusal criteria for rock*

In order to develop a criterion to estimate the refusal level of piles the final set distribution was considered in conjunction with the SPT and pile set correlations. Criteria were established for different rock lithologies due to current information suggesting this to be the more significant factor (Fig. 3). The median value of the final set distribution was used to infer the following refusal criteria from the toe SPT and pile set relationships where the depth from the surface to XW rock is 5 to 25 m (median value of 14 m):

- Sandstone: SPT $\geq$ 90
- Shale: SPT $\geq$ 160

These criteria highlight the need to be able to extrapolate beyond SPT refusal values as discussed by Look (2004).

It is expected that the criteria will generally overestimate the refusal level. This is due to the trend lines residing mostly above the data points in the range of refusal set values (ie a higher set value is estimated than actually achieved) (Fig. 5).

This general overestimation was confirmed by assessing the estimated refusal level with the actual refusal level of piles. Those piles assessed were included in the data set used in the original model development. Comparisons for all piles were not possible as the available SPT information did not extend beyond the refusal level in a number of instances; providing further evidence that the refusal level is generally overestimated using the defined criteria.

Based on the distribution an error range of -2 to 3 m was indicated to apply to the refusal criteria. In the context of estimating the required level of field investigations the borehole should be extended at least 2 m beyond the estimated level using the criteria to ensure information to an adequate depth is obtained. However, this does not include necessary allowance to verify the integrity of strata below the pile toe.

4 CONCLUSIONS

Investigation and pile driving data from bridge sites across SEQ was used to examine the effectiveness of the SPT to directly estimate the refusal level of driven piles in rock. A number of correlations were obtained between SPT information and pile set values indicating the potential application of the SPT. These correlations only resulted through independent assessment of different substrata conditions.

Pile set was generally best described as a function of both the pile toe and cumulative shaft SPT values, with the latter demonstrating greater influence. Less reliable correlations obtained for piles driven in predominantly cohesionless material indicated that the different scales of both processes influenced the estimation of set values.

The influence of the toe SPT increased when piles penetrated rock. Moreover, correlations were found also to be a function of rock lithology and weathering, which also reflect rock strength, however the relative influence of these characteristics was not conclusive due to the distribution of the data. The magnitude of final set values was generally smaller for piles penetrating rock, consistent with the practice of driving piles to refusal.

Refusal criteria based on rock lithology were established from final set values and correlations between the pile toe SPT and set values. Comparison with actual pile refusal levels indicated an additional 2 m would be necessary to ensure the investigation extended to an adequate depth. Based on these results, the following criteria for driven PSC piles of 450 to 550 mm were established as a guide to estimate the required depth of boreholes at the investigation stage where the depth from the surface to XW rock is 5 to 25 m (median value of 14 m):

- Sandstone: Drilling depth ≥ [SPT ≥ 90] + 2 m
- Shale: Drilling depth ≥ [SPT ≥ 160] + 2 m

It should be noted that these guidelines are subject to further investigation. They do not include additional drilling required to ensure the integrity of strata below the pile toe, or cater for differing pile types. They also highlight that different rock lithologies are likely to have different refusal criterions. These SPT values are also useful in estimating likely refusal levels during later design stages.

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